Neutron-Antineutron Oscillation Search with Free Neutrons

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Project X Workshop

Why use free neutrons?

Experimental requirements

Improved experiment with slow neutrons

Neutron-Antineutron Oscillations: Formalism

$\alpha \neq 0$ allows oscillations

$$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$ n-nbar state vector

$$\mathrm{H} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$$ Hamiltonian of n-nbar system

$$E_n = m_n + \frac{p^2}{2m_n} + U_n \quad ; \quad E_{\bar{n}} = m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + U_{\bar{n}}$$

Note :

- α real (assuming T)
- $m_n = m_{\bar{n}}$ (assuming CPT)
- $U_n \neq U_{\bar{n}}$ in matter and in external B [$\mu(\bar{n}) = -\mu(n)$ from CPT]

Neutron-Antineutron transition probability

For $H = \begin{pmatrix} E+V & \alpha \\ \alpha & E-V \end{pmatrix}$ $\quad P_{n\to\bar{n}}(t) = \dfrac{\alpha^2}{\alpha^2+V^2} \times \sin^2\left[\dfrac{\sqrt{\alpha^2+V^2}}{\hbar}t\right]$

where V is the potential difference for neutron and anti-neutron.

Present limit (from SuperK data+Gal theory) on $\alpha \le 2\times10^{-24}\, eV$

Contributions to V:

<Vmatter>~100 neV, proportional to density

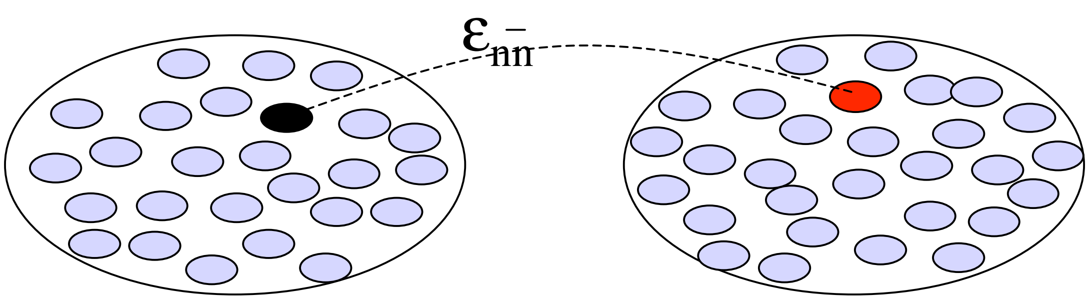
<Vmag>=μB, ~60 neV/Tesla; B~10nT-> Vmag~10^{-15} eV

<Vmatter> , <Vmag> both >>α

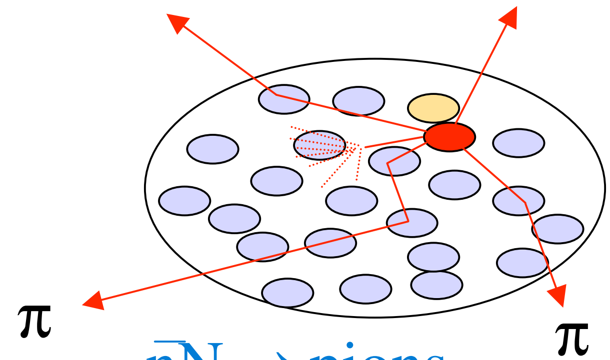
For $\left[\dfrac{\sqrt{\alpha^2+V^2}}{\hbar}t\right] << 1$ ("quasifree condition") $\quad P_{n\to\bar{n}} = \left(\dfrac{\alpha}{\hbar}\times t\right)^2 = \left(\dfrac{t}{\tau_{n\bar{n}}}\right)^2$

Figure of merit= NT^2 N=#neutrons, T="quasifree" observation time

Neutron Oscillations in Nuclei



Nucleus A $\rightarrow$ A* + $\bar{n}$



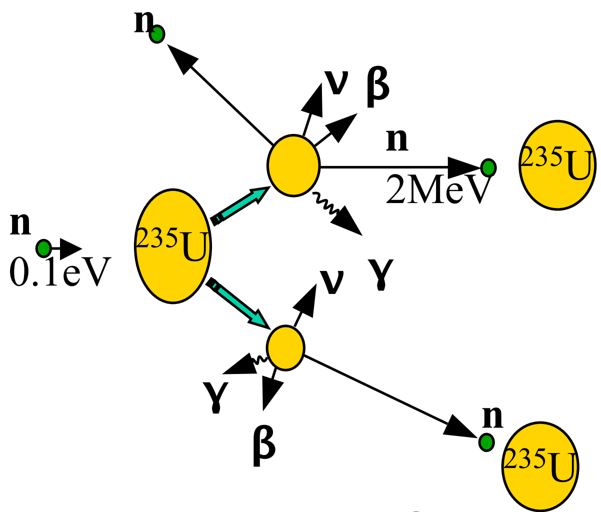
$\bar{n}$N $\rightarrow$ pions

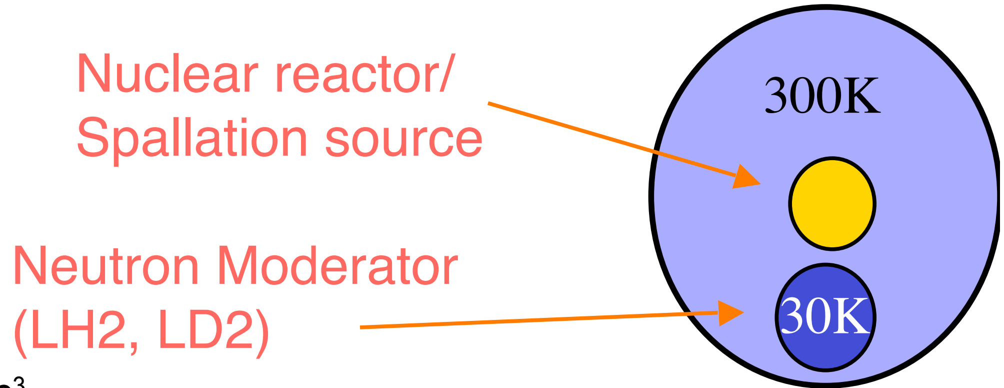
N-nbar transitions in nuclei in underground detectors: better limits now, but
(1) Backgrounds: very hard to claim a discovery
(2) Backgrounds: hard to improve limit further
(3) Some nuclear model dependence in conversion to free oscillation limit

Free Neutron Oscillations

(1) Backgrounds can be very low: antineutron annihilation vertex restricted to very small volume
(2) Experimental control over quasifree condition: oscillation can be turned off with very small change in magnetic field
(3) Sensitivity can be improved significantly using existing technology

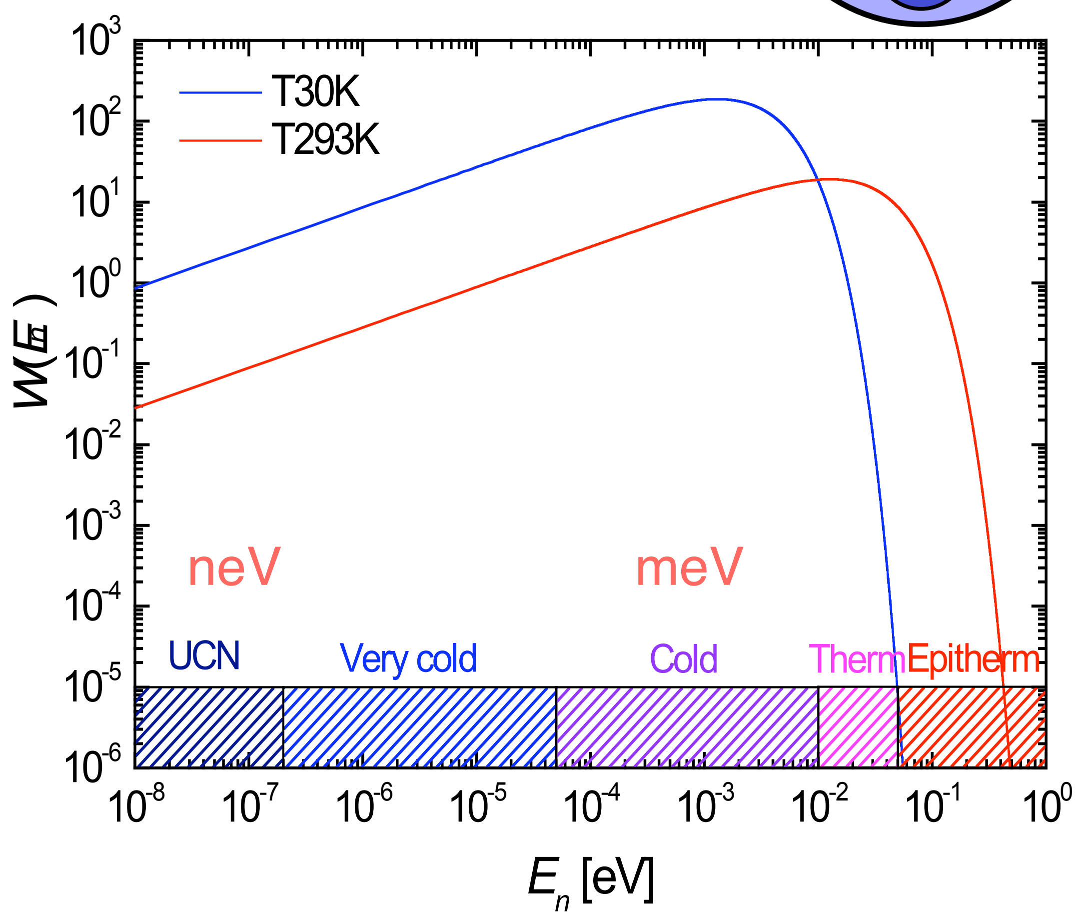
“Slow” Neutrons: MeV to neV



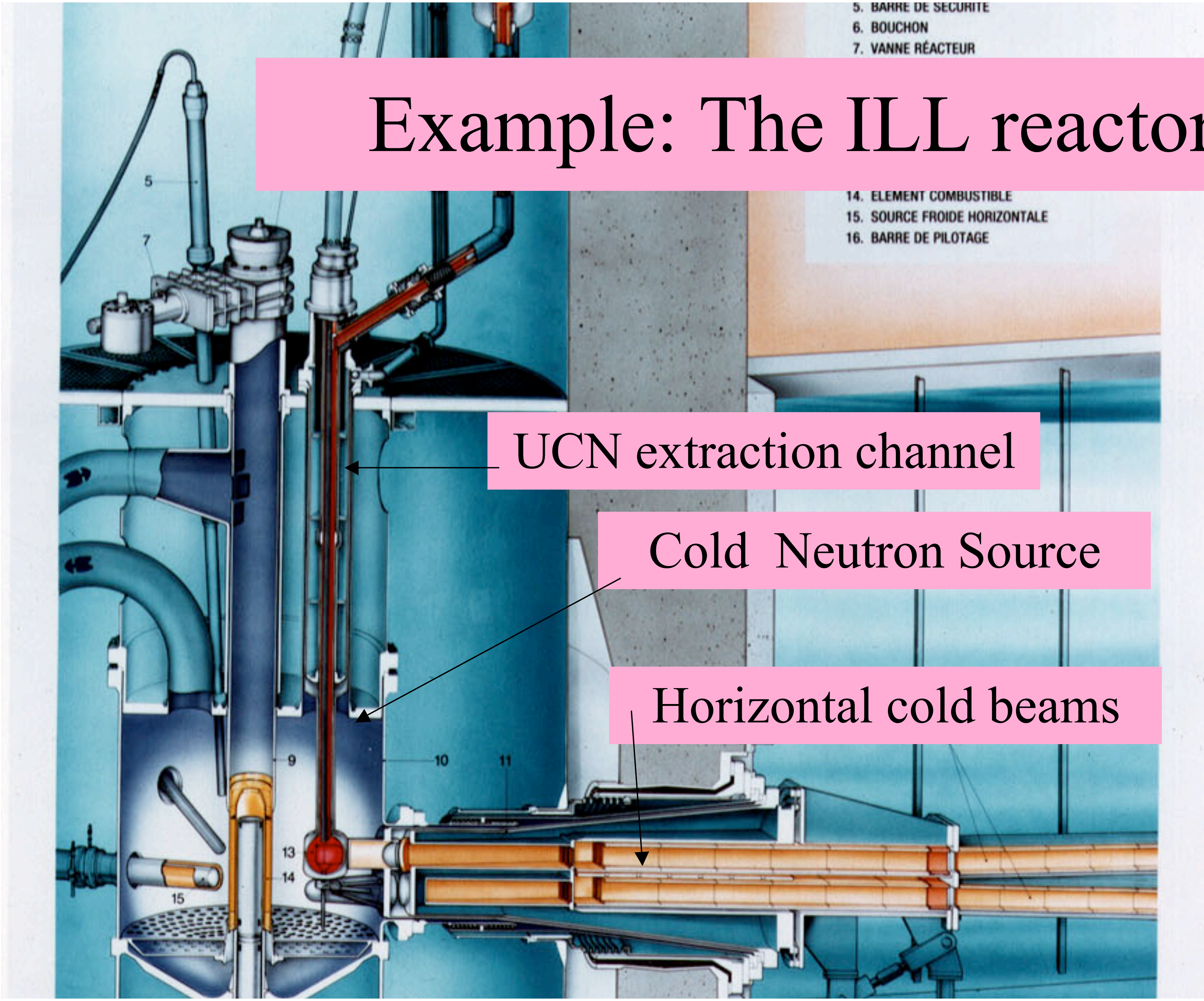


~MeV neutrons from fission or spallation, thermalized in ~ 20 collisions in ~ 100 μs

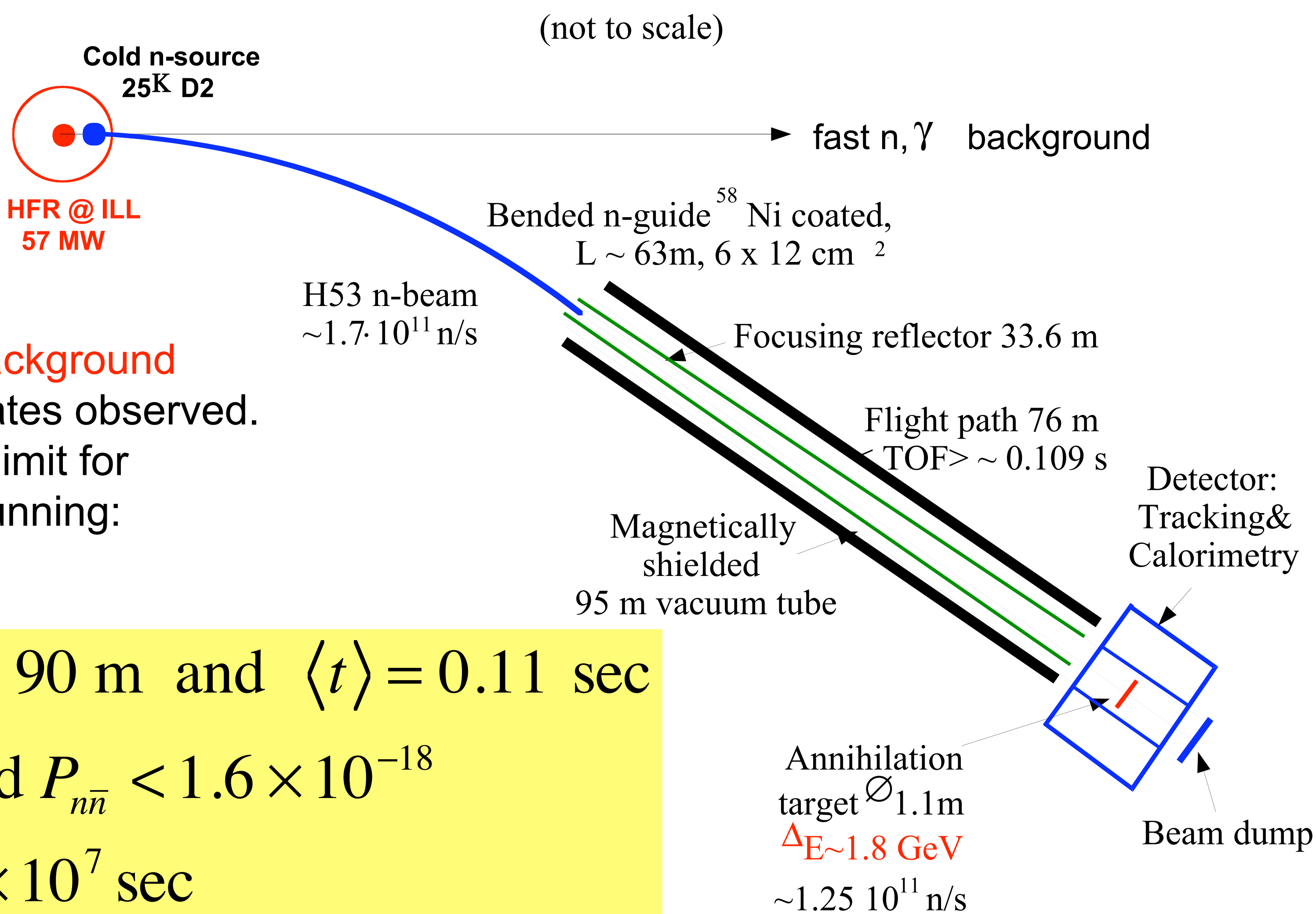
T (K)	E (meV)	λ (A)	v (m/sec)
300	25	1.6	2200
20	2	6.4	550



Example: The ILL reactor



N-Nbar search at ILL (Heidelberg-ILL-Padova-Pavia)



No GeV background

No candidates observed.
Measured limit for
a year of running:

$$\text{with L} \sim 90 \text{ m and } \langle t \rangle = 0.11 \text{ sec}$$

$$\text{measured } P_{n\bar{n}} < 1.6 \times 10^{-18}$$

$$\tau > 8.6 \times 10^{7} \text{ sec}$$

Baldo-Ceolin M. et al., Z. Phys. C63,409 (1994).

Quasifree Condition: B Shielding and Vacuum

$\mu B t \ll \hbar$ ILL achieved |B|<10 nT over 1m diameter, 80 m beam,one layer 1mm shield in SS vacuum tank, 1% reduction in oscillation efficiency (Bitter et al, NIM A309, 521 (1991). For new experiment need |B|<~1 nT

If nnbar candidate signal seen, easy to "turn it off" by increasing B

$V_{opt} t \ll \hbar$:

Need vacuum to eliminate neutron-antineutron optical potential difference.
$P<10^{-5}$ Pa is good enough, much less stringent than LIGO

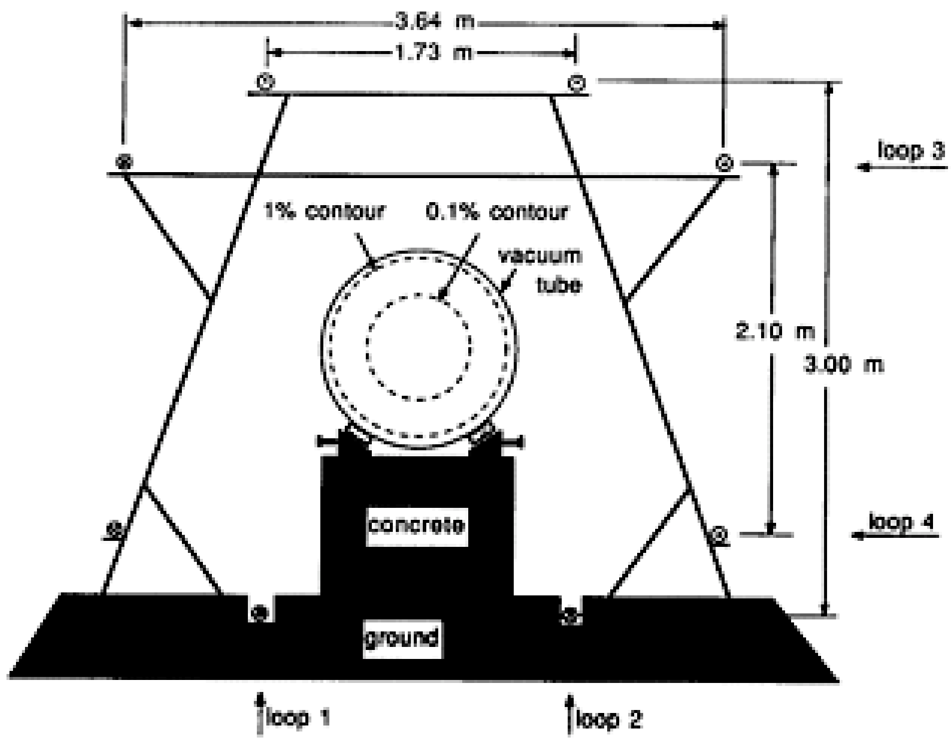
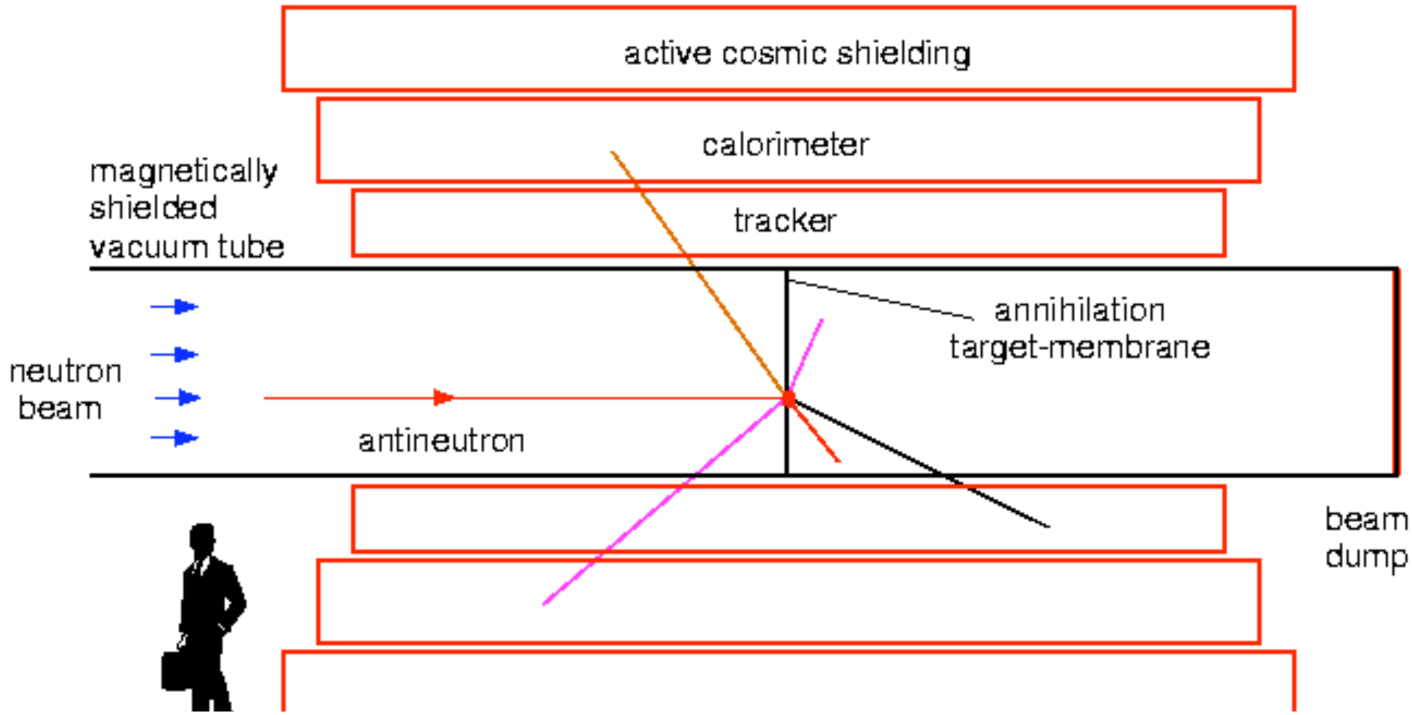


Fig. 10. The transverse field compensation system. Loops 1 and 2 are under 49 A current and compensate the horizontal field component; loops 3 and 4 are under 120 A current and compensate the vertical field component.

The conceptual scheme of antineutron detector



$$\bar{n} + A \rightarrow \langle 5 \rangle \; pions \quad (1.8\ \mathrm{GeV})$$

Annihilation target: ~100μ thick Carbon film

$\sigma_{annihilation} \sim 4$ Kb $\qquad \sigma_{nC\ capture} \sim 4$ mb

Vertex location of annihilation is precisely defined

ILL experiment saw no background

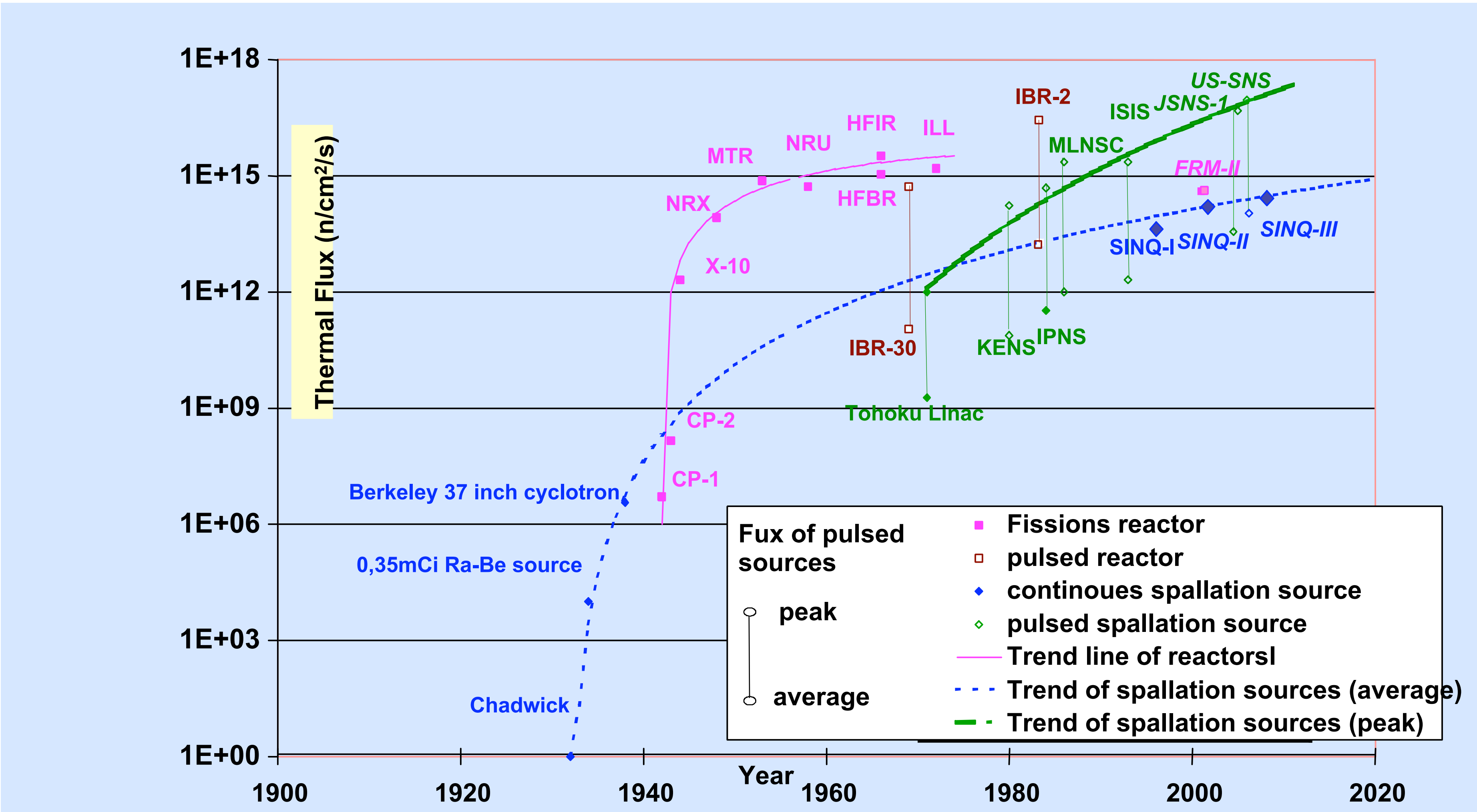
Better Slow Neutron Experiment: What do we want? (HOW DIFFICULT IS IT?)

While still keeping quasifree condition, one wants more NT^2 with nbar detector watching the annihilation surface

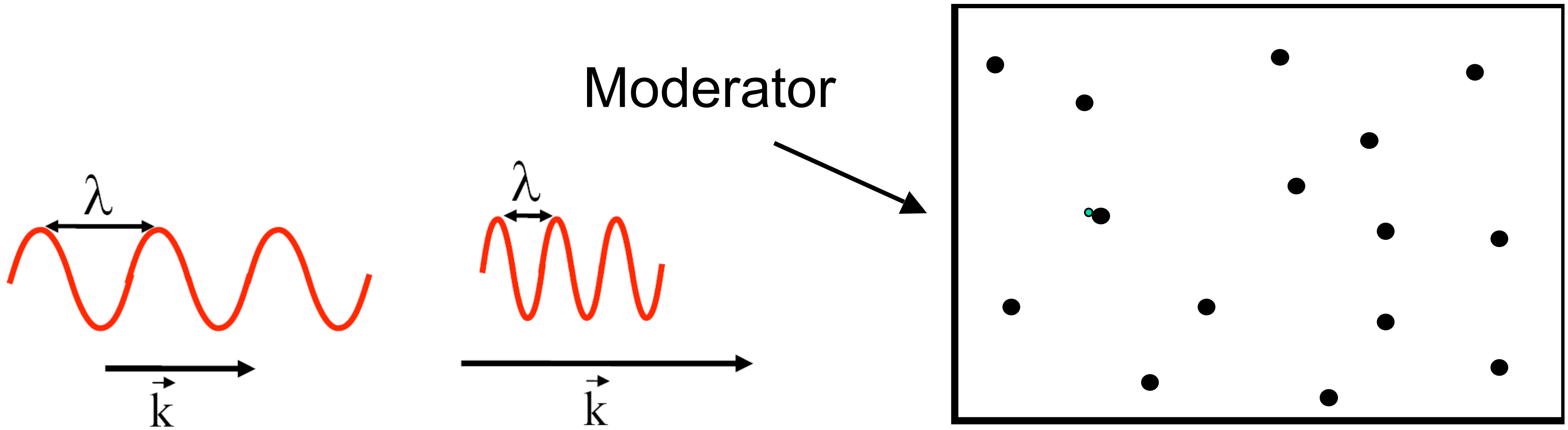
- higher cold neutrons flux from source DIFFICULT
- slower cold neutron energy spectrum DIFFICULT
- more efficient extraction of cold neutrons with optics to quasifree flight/detector GREAT PROGRESS
- longer “quasifree” flight time (YES, SOME GAIN)
- longer experiment operation time YES (ILL only ran 1 year)

<u>For cold neutrons</u>: Improvement on ILL experiment by factor of ~1000 in transition probability is possible with existing n optics technology, sources, and moderators

Max neutron flux/brightness: ~unchanged for ~4 decades



Neutron flux is increasing only slowly with time R. Eichler, PSI



Why is it hard to make colder neutron spectra from cold sources?

1. Cryogenic engineering (heat loads, conductivity/heat capacity…)
2. For cold neutrons with $\lambda > d$, $\sigma_{el} >> \sigma_{in}$, most collisions elastic
3. Frozen materials required to lower neutron T also freeze inelastic modes
4. Radiation damage causes cryogenic solids to decompose or explode
5. Phonon phase space decreases as ω^3, need to find other inelastic modes

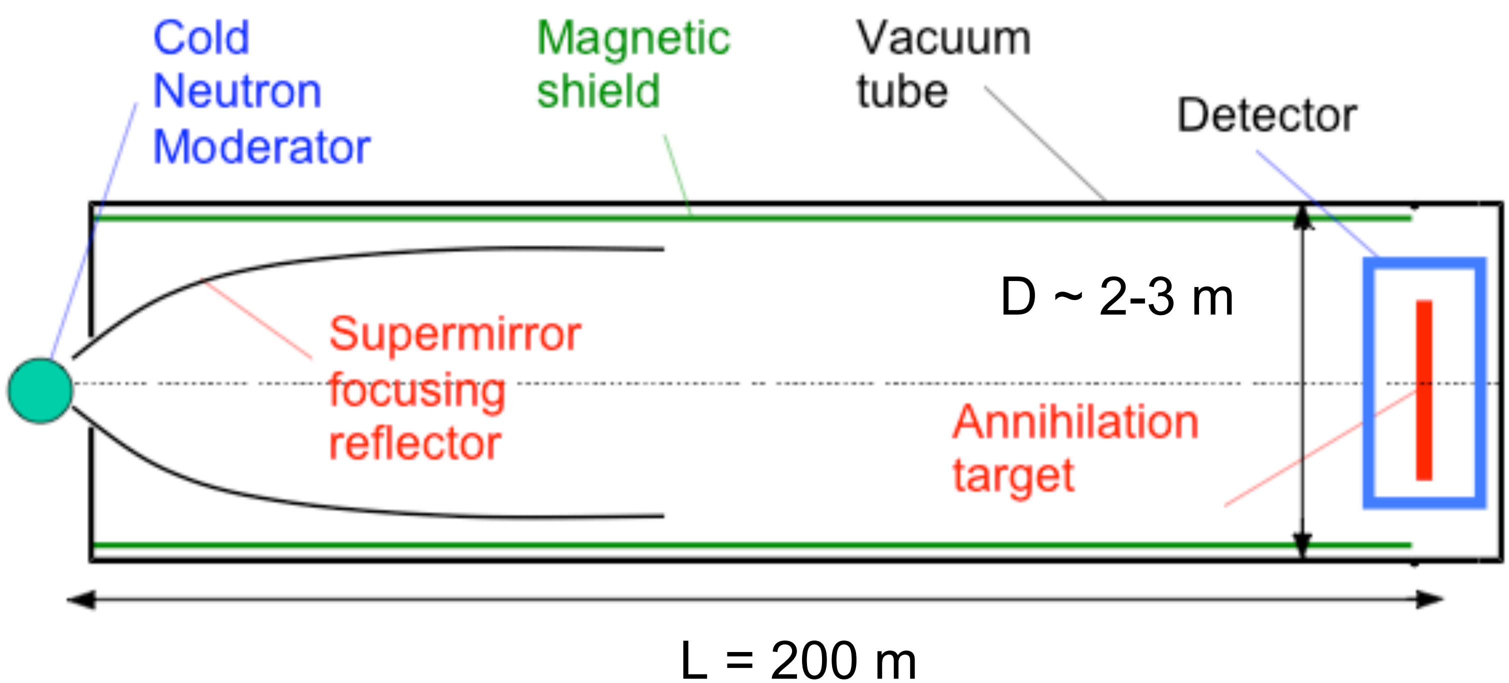
Research on better slow neutron moderators in progress

"Ultracold Neutrons" special case

Better Cold Neutron Experiment (Horizontal beam example)

- need cold neutrons from high flux source, access of neutron focusing reflector to cold source, free flight path of ~200m

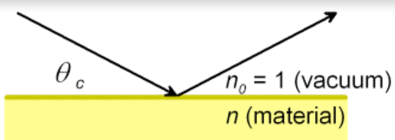
Image of n source is blurred by finite source and neutron velocity dispersion -> limits practical length of a horizontal experiment

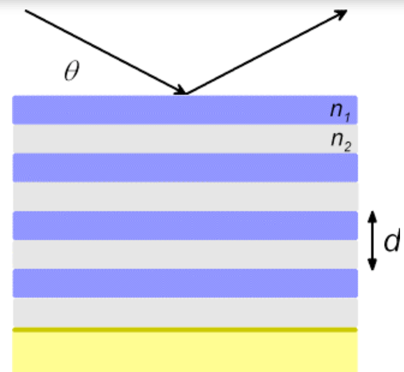


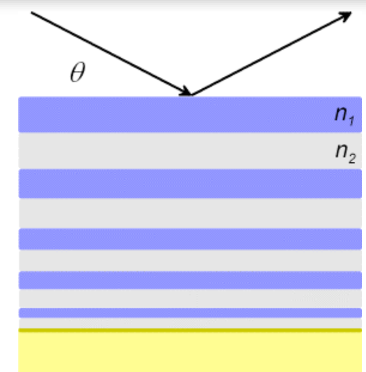
concept of neutron supermirrors: Swiss Neutronics

neutron reflection at grazing incidence (< ≈2°)

@ smooth surfaces	@ multilayer	@ supermirror

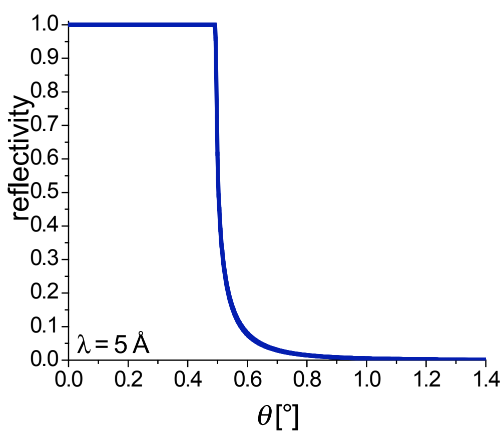


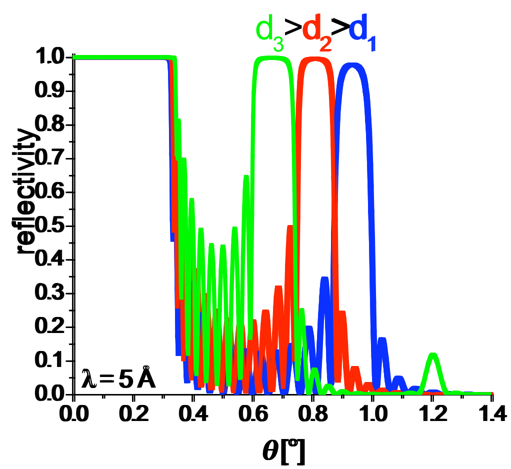


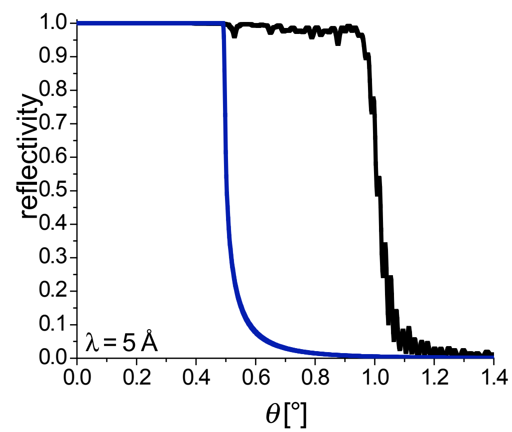


- refractive index n < 1
- total external reflection
  e.g. Ni θ_c = 0.1 °/Å

$$\lambda = 2d\sin\theta$$





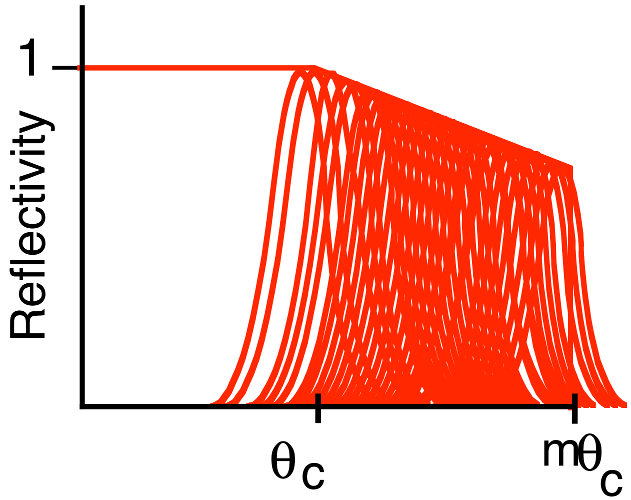


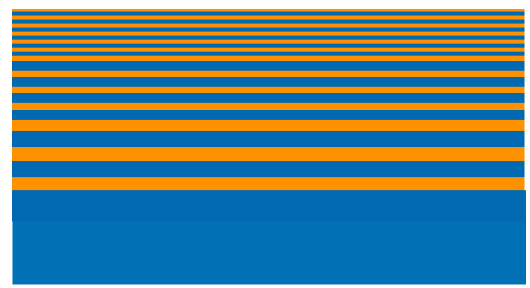
m=1 $\quad \theta_{critical} \rightarrow m\theta_{critical}$ $\quad$ m=2

“Supermirrors”: $\theta_{critical} \rightarrow m\theta_{critical}$

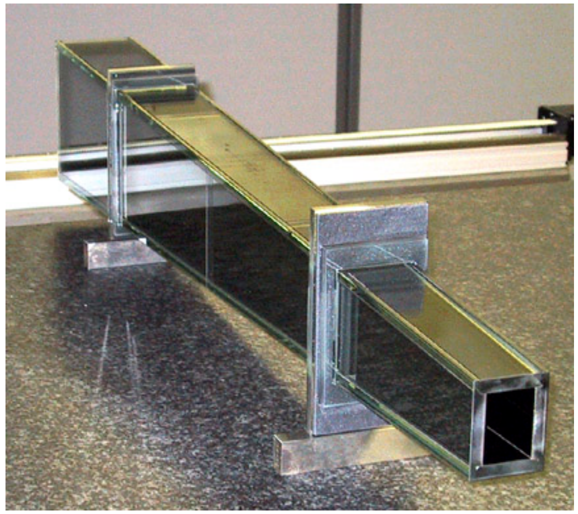
Commercial Supermirror Neutron Mirrors are Available With m ≈ 3 - 4.

Phase space acceptance for straight guide ∝m^2, more with focusing reflector





Multilayer mirror



“Items of commerce”

Neutron mirror technology (for the most part) still involves static mirrors -> no compression of phase space density (Liouville)
But supermirrors with higher m exist (M. Shimizu talk)

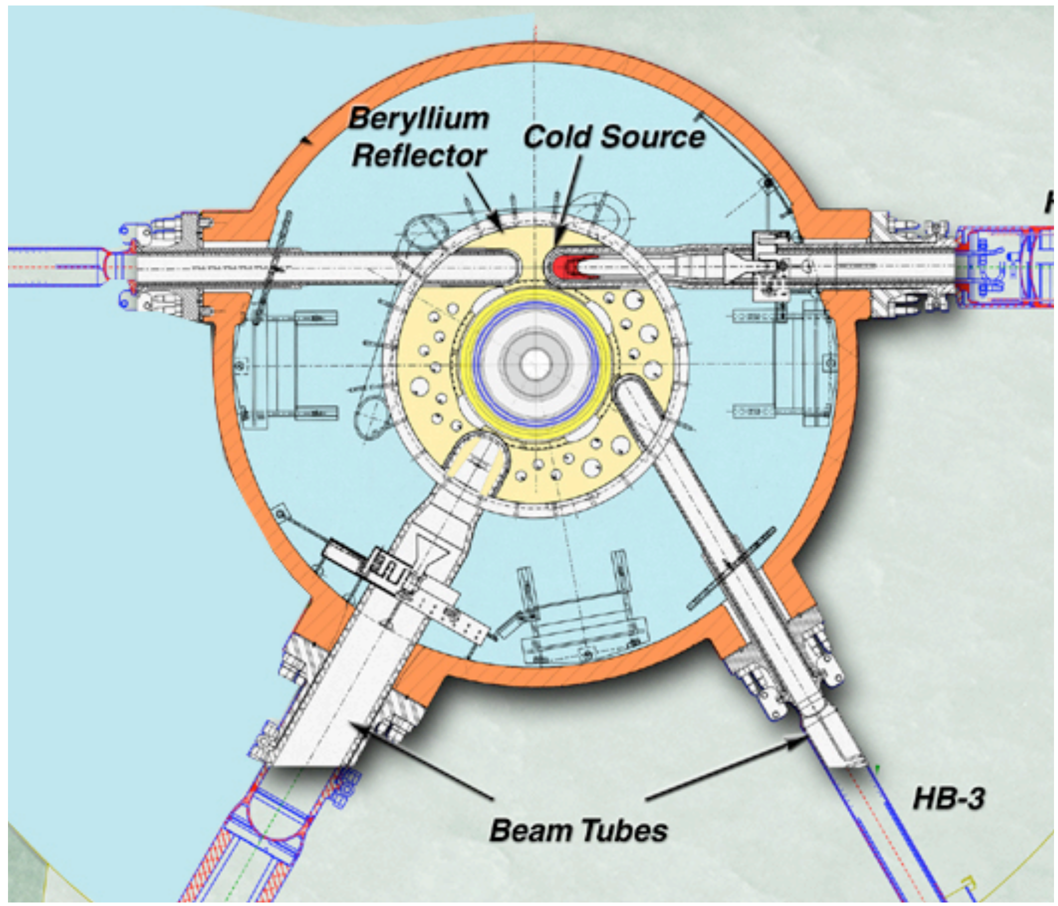
“Slow neutron adaptive optics” does not yet exist
(see P.Boni, NIM A586, 1 [2008] for future hopes)

New Experiment at Existing Research Reactor?

- need close access to cold source to fully illuminate elliptical reflector. Not easy to create in an existing user facility

- Requests to all >20 MW research reactors with cold neutron sources: no takers.

- Only possibility is for a "green-field" neutron source



Cutaway view HFIR reactor at ORNL

Sources of ~x1000 Improvement on ILL Experiment with Cold Neutrons

-increased phase space acceptance of neutrons from source (using m≥3 supermirrors): x~60->?

-larger moderator:
x~10 years (ILL 1 year)

-increase neutron free-flight time (t^2):
x~4-10 (horizontal, limited by gravitational defocusing)

-source brightness:
x~1/4 (horizontal, FNAL)

-cold moderator gain:
x~2

NNbar Summary

New physics beyond the SM can be discovered by NNbar search

Improvement in free neutron oscillation probability of a factor of ~1,000 is possible

If discovered:

- $n \rightarrow$nbar observation would violate B-L by 2 units, establish a new force of nature, illuminate beyond SM physics, and may help to understand matter-antimatter asymmetry of universe

If NOT discovered:

- will set a new limit on the stability of "normal" matter via antimatter transformation channel. Will constrain some scenarios for B-L violation and "post-sphaeleron" baryogenesis

Summary

New physics beyond the Standard Model can be discovered by NNbar search

Experiments with free neutrons possess very low backgrounds (sharp vertex localization): ILL experiment observed no background. Interpretation of result is independent of nuclear models. Any positive observation can be turned off experimentally with the application of a small magnetic field.

Sensitivity of free neutron experiment for NNbar transition rate can be improved by factor of ~1000 using existing technology [Combination of improvements in neutron optics technology, longer observation time, and larger-scale experiment]. Further improvements in a free neutron experiment can comes from neutron optics technology development.

US high-energy intensity frontier complex could in principle provide the type of dedicated source of slow neutrons needed for NNbar experiment.